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Laser Cooling and Trapping of Atoms and Particles

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6. AUTHOR(S): Professor Steven Chu

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13. ABSTRACT (Maximum 200 words)

The program was to explore the use of light to manipulate atoms and other particles, particularly the cooling andn trapping of atoms, the manipulation of biological molecules, and the creations of new devices based on these techniques. (SEE REPORT FOR MORE ACCOMPLISHMENTS)

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January 16, 1992

AFOSR Final Project Report for the grant:

"Laser Cooling and Trapping of Atoms and Particles"
AFSOR-88-0349
Sept. 1, 1988 - Aug. 31, 1991
P.I.: Steven Chu, Stanford University

The program was to explore the use of light to manipulate atoms and other particles, particularly the cooling and trapping of atoms, the manipulation of biological molecules, and the creation of new devices based on these techniques.

Accomplishments that have come out of the three year proposal period include:

1) The development of a new theory of laser cooling, commonly known as "polarization gradient cooling". The theory (also developed independently by J. Dalibard and C. Cohen-Tannoudji) explains how light can cool atoms to temperatures more than 2 orders of magnitude below the cooling limit based on the original Hänsch/Schawlow cooling scheme.

2) A series of experiments that tested the new cooling theory in one-dimensional geometries. The work also included the first quantitative demonstration of the theory for two-level atoms.

3) The discovery of cooling to sub-Doppler temperatures without polarization gradients in weak magnetic fields, and the explanation within the context of the new cooling theory. Metcalf's group also explored this work after our initial discovery.

4) The demonstration of an atomic fountain and precision microwave spectroscopy with that fountain. The work showed that it is possible to significantly improve the cesium time standard, perhaps by as much as 3 orders of magnitude, and has prompted 8 other groups to try to develop a better time standard based on an atomic fountain of cesium atoms.

4) The invention and demonstration of an atom funnel that greatly increased the brightness of a cold atomic beam of atoms by over 5 orders of magnitude. The creation of an atom trampoline, where cold atoms were dropped onto a evanescent wave of light extending out of a totally internally reflected wave. We have shown that atoms will bounce back elastically, and with a minor modification, one can make an atom trap based on gravity and a concave atomic mirror.

5) The invention and demonstration of a new type of atom interferometer. The interferometer is based on stimulated Raman transitions between ground states of atoms

in an atomic fountain and adapts ideas in nuclear magnetic resonance to atom manipulation. We were one of four groups to report atom interferometers within the space of 3 months, but our work is distinguished from the other efforts. While the other groups reported interference fringes as a demonstration of atom interferometry, we were able go beyond the demonstration stage and measure the acceleration of gravity of an atom to a precision of 3 parts in 10^6 in our initial work. We have subsequently increased the precision to 3 parts in 10^8. In the next generation experiment, we believe that we can exceed a part in 10^{11}.

If the experimental apparatus is moved up by 1 millimeter from the center of the earth, g will change by 1 part in 10^9. This sensitivity will have implications in the measurement of vertical land mass movement (for earthquake prediction), the height of ocean levels (for global warming studies), and for oil exploration. In combination with ranging with the GPS (global positioning satellite) system, which has a resolution of a few cm, one will be sensitive to water table changes, the underground flow of lava near a volcano, etc.

6) The demonstration of the optical manipulation of DNA with optical tweezers. We have shown that a single molecule of DNA can be manipulated with optical traps provided that small dielectric spheres are attached to the ends of the DNA. We are currently testing many of the basic tenants of polymer physics at the single molecular level with this technique. Later we intend to attack some of the biological problems that can be addressed with this technique. In collaboration with Prof. James Spudich in the Biochemistry Department of the Medical School at Stanford, we are beginning a program in both DNA manipulation and the study of the actin/myosin system, the molecules responsible for muscle contraction.

7) Several patents have been filed as a result of this work:
(i) In collaboration with Prof. Carl Wieman and William Swann (student) of the University of Colorado, the Research Corp. has filed a patent on "an improved frequency standard using an atomic fountain of optically trapped atoms."
(ii) Stanford University has filed and received a patent on a "method and apparatus for optically manipulating microscopic particles", with Steve Kron, (former graduate student) and myself. The patent covers the manipulation of DNA with optical tweezers.
(iii) Stanford intends to file a patent on an "atomic interferometer with light pulses" to be filed with M. Kasevich (student).

The work supported by the Air Force has received wide recognition. Over 60 plenary talks, invited talks and university colloquia have been given about this work in the last three years. Among these talks are a series of lectures given a Harvard (the Morris Loeb Lectures), another series given at the Collège de France, a series of lectures at the Enrico Fermi Summer School in Varenna, Italy on Laser Cooling in 1991 and another series to be given in the summer of 1992 on the Frontiers of Laser Spectroscopy. Other talks included the 1991 Public lecture of the Australian National Academy of Sciences, the 49th Richtmeyer Memorial Prize lecture of the APS and the AAPT, a plenary talk at the first Unity Day Lectures of the APS April General meeting, talks to commemorate the University of New Mexico's 100th Anniversary, the dedication of the Univ. of Michigan's new Laser Center, the 25th anniversary of the invention of the dye laser at IBM, etc.

In addition to the papers written for the experts, several papers have been written for the general audience. These include a long review article for *Science* and the cover story for the Feb. 1992 issue of *Scientific American.* A 17,000 word article for the Encyclopedia Britannica covering all aspects of "Spectroscopy", shorter entries for the *Encyclopedia of Physics* and the *McGraw Hill Encyclopedia of Science and Technology* have also been written. News stories of our work have appeared in *Physics Today*, *Scientific American*, *Nature*, *Science*, *Optics News*, and *Time Magazine*. Our work has been featured a number of times in the annual scientific summaries of noteworthy achievements in both physics and optics.

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Born February 28, 1948
Married, two children

Education: A.B., Mathematics, University of Rochester, 1970
B.S., Physics, University of Rochester, 1970
Ph.D., Physics, University of California at Berkeley, 1976
Thesis: Measurement of the $6^2P_{1/2}-7^2P_{1/2}$ Forbidden M1 Transition in Atomic Thallium
Thesis Advisor: Professor Eugene D. Commins

Employment: Postdoctoral Research Fellow,University of California at Berkeley, 1976-1978
Member, Technical Staff, Electromagnetic Phenomena Research Bell Laboratories, Murray Hill, 1978-1983
Head, Quantum Electronics Research Department AT&T Bell Laboratories, Holmdel, 1983-1987
Professor of Physics and Applied Physics, Stanford University, 1987-present
Theodore and Frances Geballe Professor of Humanities and Sciences, Stanford University, 1990-present
Chair of the Physics Dept., Stanford Univ., 1990-present

Summary of Research Experience and Interests:

- Parity nonconservation in atomic physics
- Energy transfer and exciton dynamics in solids
- Anderson Localization, Mott transitions
- Picosecond spectroscopy
- High resolution laser spectroscopy
- Positronium-surface interactions
- Positronium and muonium spectroscopy
- Laser cooling and trapping of atoms
- Manipulation of Biological Molecules
- Microscopy

Steven Chu (continued)

Fellowships, Honors, Professional Affiliations, Lectureships:

The Stoddard Prize in Mathematics,
University of Rochester
The Stoddard Prize in Physics,
University of Rochester
Woodrow Wilson Fellow

National Science Foundation Predoctoral Fellow
National Science Foundation Postdoctoral Fellow
Fellow of the American Physical Society

Am. Phys. Soc., Broida Prize for Laser Spectroscopy,
1987
Morris Loeb Lecturer, Harvard University, 1987-1988
Special Visitor to JILA, 1989

APS/ AAPT Richtmyer Memorial Prize Lecture, 1990
Visiting Professor, Collège de France, 1990
Fellow of the Optical Society of America

Partial List of Professional Service:

Chair, Laser Science Topical Group of the
Am. Phys. Soc. 1989-90
Vice-Chair, LSTG, 1989-90
Associate Editor, Optics Letters
Co-editor of the J. Optical Soc. Am. B, Special
issue on "Laser Cooling and Trapping of Atoms"
Int. Conf. on Quantum Electronics, Program co-chair,
1990
Conf. on Quantum Electronics Laser Science co-chair,
1992
Program Committee Member: DAMOP 1985-87, QELS 1989,
ICAP 1988, IQEC 1986-88
Member of the National Science Foundation Physics
Advisory Council
Conference co-chair of the 1993 US-Japan Conference
on Laser Science

Partial List of Stanford University Service:

Member of the Appointments and Promotions Committee
of the School of Humanities and Sciences, 1989-90
Member of the Cabinet Committee on Budget and
Strategic Planning, 1991-92
Member of the Stanford President Selection Committee